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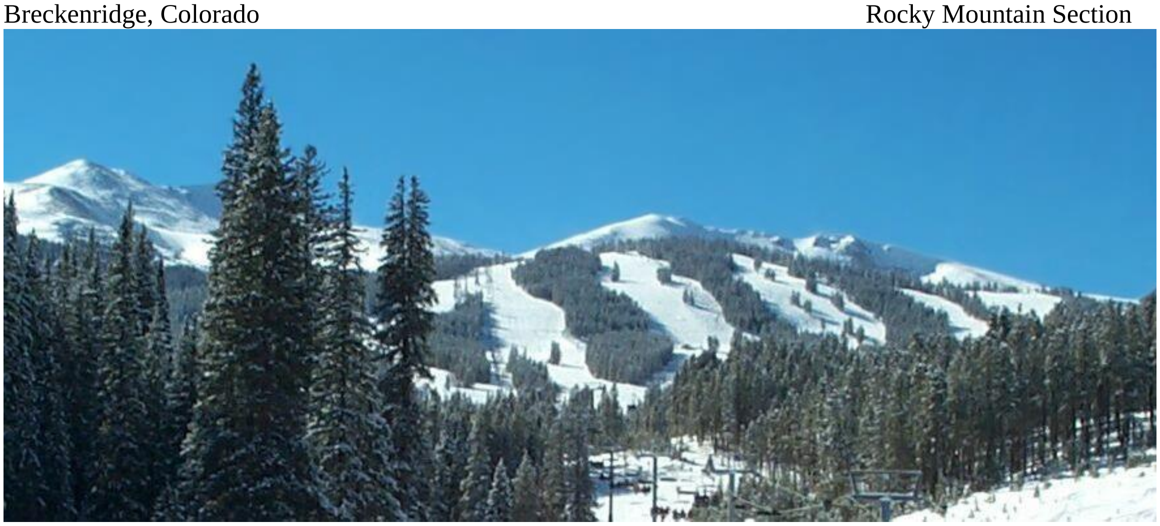

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Post-Flight Analysis of GPSR Performance During Orion Exploration Flight Test 1

Lee Barker[†], Harvey Mamich[‡], John McGregor*

On 5 December 2014, the first test flight of the Orion Multi-Purpose Crew Vehicle executed a unique and challenging flight profile including an elevated re-entry velocity and steeper flight path angle to envelope lunar re-entry conditions. A new navigation system including a single frequency (L1) GPS receiver was evaluated for use as part of the redundant navigation system required for human space flight. The single frequency receiver was challenged by a highly dynamic flight environment including flight above low Earth orbit, as well as single frequency operation with ionospheric delay present. This paper presents a brief description of the GPS navigation system, an independent analysis of flight telemetry data, and evaluation of the GPSR performance, including evaluation of the ionospheric model employed to supplement the single frequency receiver. Lessons learned and potential improvements will be discussed.

Introduction and Background

On 5 December 2014, the first test flight of the Orion Multi-Purpose Crew Vehicle executed a unique and challenging flight profile including an elevated re-entry velocity and steeper flight path angle to envelope lunar re-entry conditions. The flight consisted of two orbits lasting approximately 4.5 hours. The first phase of the two orbits is in low Earth orbit (LEO). The second of the two orbits placed the vehicle into a highly elliptical orbit (apogee radius of about 12,000 km) that results in near lunar-return re-entry conditions [1][2].

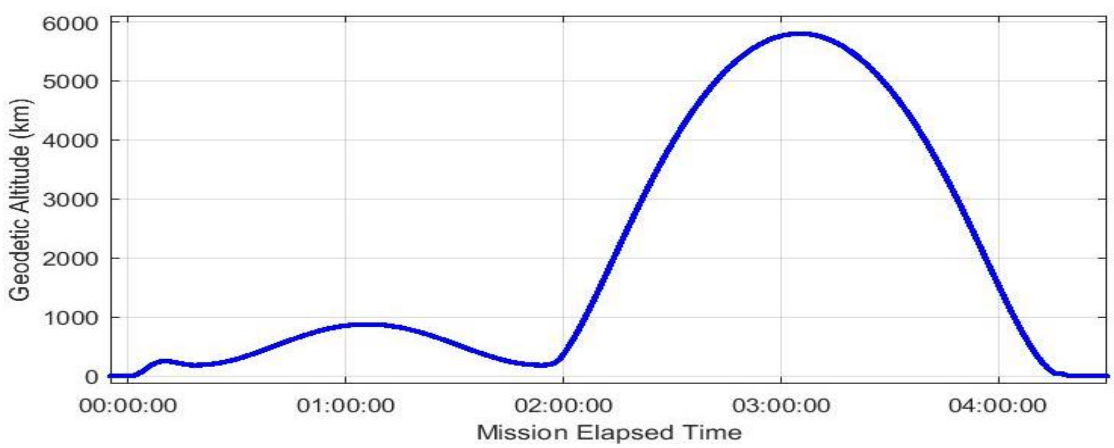

Figure 1-EFT1 Mission Trajectory Altitude Profile

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By design, many GPSR measurements collected during flight include either or both ionospheric delays and tropospheric delays. Additionally, Orion was actively maneuvering throughout the flight, introducing un-modeled disturbances.

Ionospheric delay modeling for single frequency users remains challenging. Ionospheric delay modeling consists primarily of estimating the Total Electron Content (TEC) of the ionosphere along a path between the GPS satellite and the space platform receiver. Electron density models can be physics based, empirical-based, or a combination of both. In general, the ionospheric models are developed for the terrestrial user. All available models will have some level of uncertainty due to the many variations in local space weather that are encountered in real data [3].

Tropospheric delay modeling is a challenge for all GPS users, regardless of whether they are single or dual frequency. For space users, it is generally recommended that any line-of-sight (LOS) path to a GPS space vehicle (SV) that pass through the troposphere be masked from the any filter solution, as the very nature of a space user encountering the troposphere places the LOS at low elevation angles where the tropospheric delay models have the highest uncertainty.

GPS SV group delay correction, whose parameters are contained in the GPS signal-in-space (SIS) navigation message, must be accounted for in single frequency measurements, as the GPS broadcast clock parameters are referenced to the dual frequency (L1/L2) phase center. Note that group delay is calibrated for a ground user and group delay error increases as the LOS moves farther from mainbeam center as in the case of a space user.

Relativistic corrections for motion of the GPS SV and the receiver are accounted for in the analysis. Note that the Orion pseudo-range data is not corrected for receiver relative motion by the Orion navigation filter. This is a small error term as compared to other error budget terms.

Line path delays for the Orion GPSR antenna cables are included in the filter solution in the independent analysis.

Attitude and the associated antenna moment arm for each antenna is not included in the independent analysis. The moment arm error can be on the order of a few meters. Likewise, inflight thruster disturbances and maneuvers are assumed unknown for analysis purposes.

Orion GPS Navigation System Overview

The Orion GPSR is an all-in-view L1 frequency Course Acquisition (C/A) code tracking GPS receiver with 24 tracking channels. The primary purpose of the GPSR is to acquire, track, decode, and process GPS signals from an antenna subsystem and provide GPS LOS measurements to the Orion navigation system. The GPSR measurement set includes pseudorange (PR), and deltarange (DR). On-board models correct the measurements for ionospheric and tropospheric propagation delays. GPS SV group differential delays are obtained from the GPS navigation message in the SIS. The GPSR produces least squares single point position, velocity, and time (PVT) solutions, while the GPSR measurements are processed by an external navigation filter which also includes an inertial measurement unit (IMU) for an improved navigation solution. Filter states include position, velocity, clock bias, clock rate terms, and various IMU errors. Further information on the Orion navigation system can be found in [1].

The Orion GPSR is also equipped with fast acquisition technology originally developed by the NASA Goddard Space Flight Center, and implemented by the manufacturer on an ASIC which simultaneously searches across multiple frequencies for a GPS signal which is strong enough to track. The use of this technology greatly simplifies operations and the integration of the GPSR within the Orion navigation system, and eliminates the need for the onboard or ground navigation systems to provide any track acquisition aiding or initialization data (position, time, or almanac) to the GPSR.

Analysis Methodology

Analysis performed in this independent assessment includes comparison of least squares single point solutions to the Orion telemetry solutions, comparison of uncorrected vs corrected measurements in single point solutions, and comparison of filtered solutions to the Orion telemetry solutions.

The independent filter tool used for this analysis is the (Precise Orbit Kalman Estimator) POKEy from the Lockheed Martin (LM) NAVSIM toolset [4]. POKEy is capable of solving in either inertial or rotating reference frames. Filter states in POKEy include position, velocity, clock bias, and clock rate. Additional available states include LOS range biases.

A dual frequency GPS receiver can remove the ionospheric delay from the pseudorange measurements providing an iono-free solution, which for the purposes of comparing to single frequency measurements could be called truth in the absence of other un-modeled delays [5].

In order to provide a level of confidence in the tools used in this analysis, on-orbit measurements from a Blackjack GPS receiver flying on the GRACE program have been processed as both dual frequency data to obtain the iono-free solution, and as single frequency data using various ionospheric models. By doing so, an understanding of ionospheric model error in measurement filtering is better understood in the case of the GRACE data where ‘truth’ from dual frequency data is known, and in the case of the Orion data, where only single frequency data is available. The GRACE spacecraft are in LEO.

Figure 2 shows an example of the GPS SV pseudo-range residuals (pre and post) for one GPS SV (PRN4) in the following cases: 1) L1/L2 iono-free measurements, 2) L1 only measurements using an ionospheric model with range bias states, and 3) L1 only measurements using an ionospheric model with no range bias states. The difference between the solved for L1/L2 ionospheric delay correction and the ionospheric model is also shown. The time span where the ionospheric model error is dynamic occurs during the mid-latitude-equatorial-crossing portion of the orbit, where ionspheric behavior is known to be most unpredictable.

The observed L1 path delay due to passage through the ionosphere using the dual frequency ionosphere path delay equation [6] is:

$$\Delta PR = \frac{PR_{L2} - PR_{L1}}{1-\gamma} \text{ where } \gamma = \left(f_{L1}/f_{L2}\right)^2 = (1575.42/1227.6)^2 .$$

It should be noted that ΔPR is typically referred to as ionosphere delay correction, but in reality, it also includes group delay difference between L2 and L1.

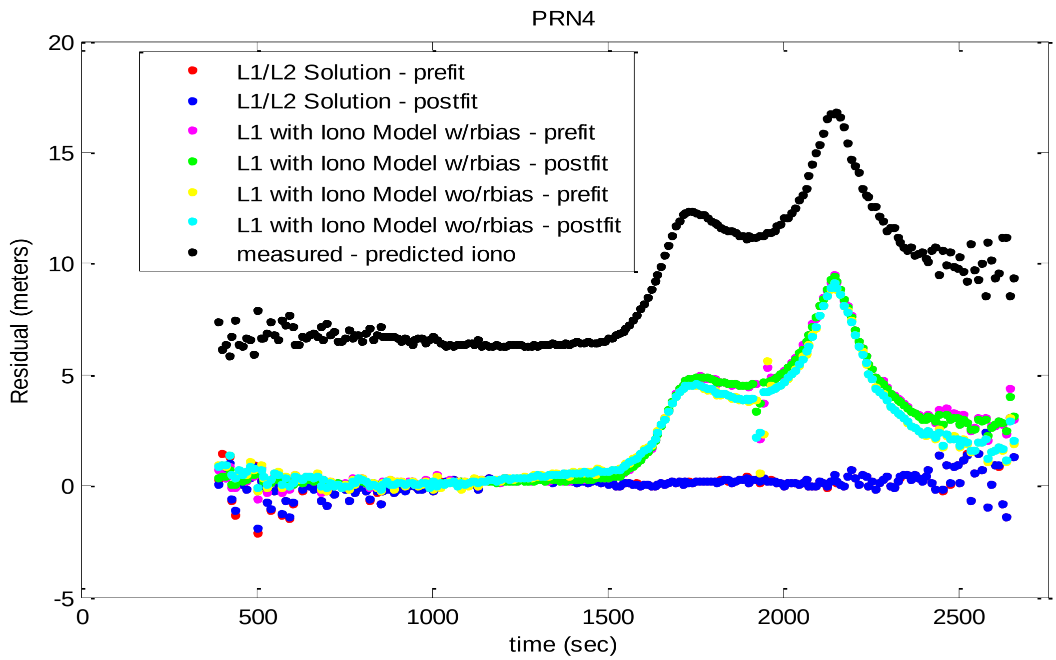

Figure 2 – GRACE data filter measurement residuals, L1/L2 vs L1 only

Ephemeris solutions for L1 only filtering vs L1/L2 solutions are compared in Figure 3. While there are numerous tuning parameters and filter state combinations that could be studied, within the limited scope of time for this analysis, the best comparison with the dual frequency L1/L2 solution using position, velocity, clock (bias and rate), delta range, and range bias states was achieved with the L1 only solution using position, velocity, clock (bias and rate), and delta range states. The plot results are intended to provide an expectation of the filter performance on the Orion data, which has no dual frequency solution to compare with.

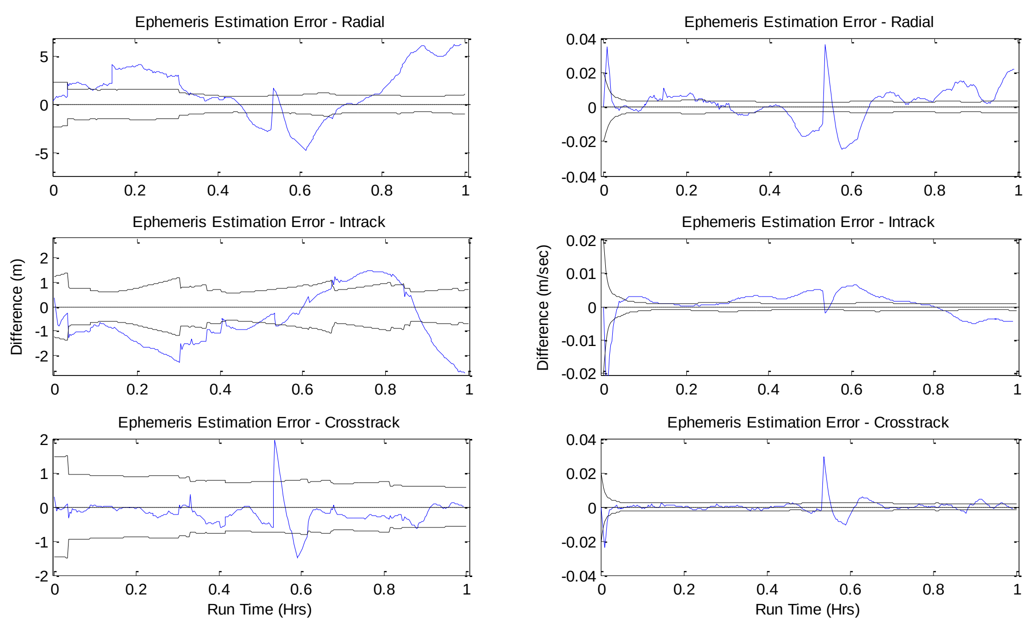

Figure 3 – GRACE data L1 only filter solution vs L1/L2 filter solution

Observations and Analysis

Orion GPSR observation data includes an uncorrected, or raw, measurement, calculated measurement corrections (ionospheric delay, tropospheric delay, L1 group delay, relativistic correction for the GPS SV, and GPS SV clock correction) and a corrected measurement. The Orion navigation filter processes the corrected measurements. The NAVSIM POKEy filter processes raw measurements, applying the correction terms above (and relativistic correction for receiver motion) in its filter process.

Prior to attempting to process Orion data, the correction terms from Orion telemetry were compared to the correction terms derived by POKEy from the GPS broadcast navigation message and from ionospheric and tropospheric models. The following observations are noted:

GPS SV clock corrections from the broadcast navigation message matched Orion telemetry to within millimeters. L1 group delay from the broadcast navigation message matched Orion telemetry to within a few millimeters. Calculated relativistic corrections using equations from [3] matched Orion telemetry. Antenna line path delays used in POKEy were set by database to match the values used by Orion flight software (FSW). A simple tropospheric model applied in POKEy matched very closely the telemetry values for tropospheric delay when these were present. Only the ionosphere model prediction comparisons produced noteworthy differences. As previously noted, the POKEy includes the receiver relativistic motion in its solution while the Orion filter does not. Figure 4 contains an example of the Orion ionosphere model prediction verses the Klobuchar model implemented in POKEy for PRN13.

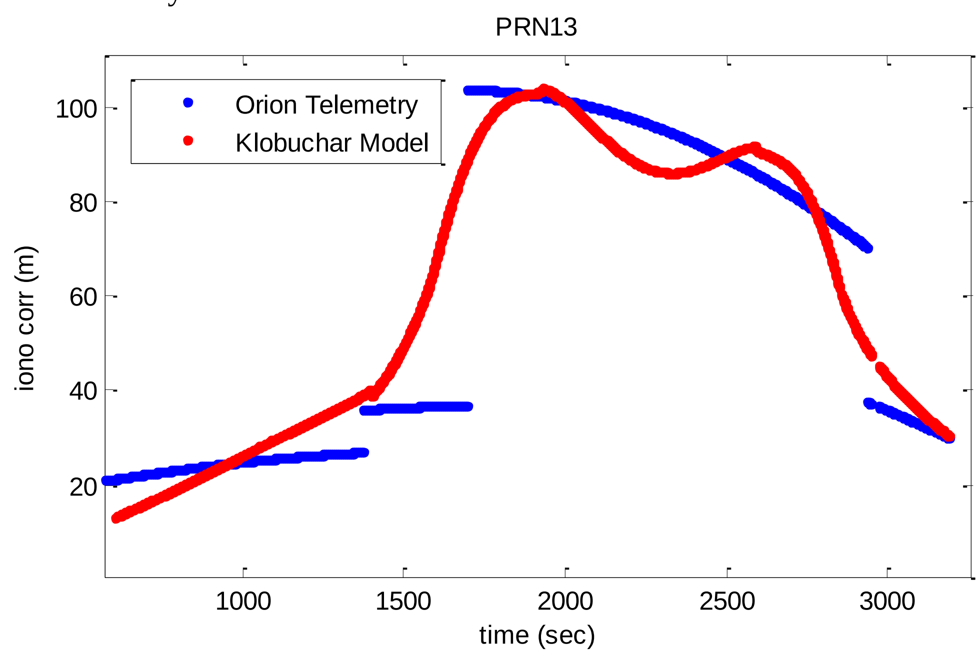

Figure 4 - Orion Klobuchar Ionospheric Model vs POKEy Klobuchar Ionospheric Model

The discrete jumps in the Orion ionospheric model data shown in Figure 4 are due to the coarseness of the onboard model grid. Improvements in the Orion ionospheric model are under consideration by the Orion program [1].

Single Point Solution Analysis

Single point solutions using uncorrected and corrected measurements were compared with the GPSR solutions provided in telemetry. The uncorrected measurement comparison did not include moment arm corrections for antenna to cm offsets.

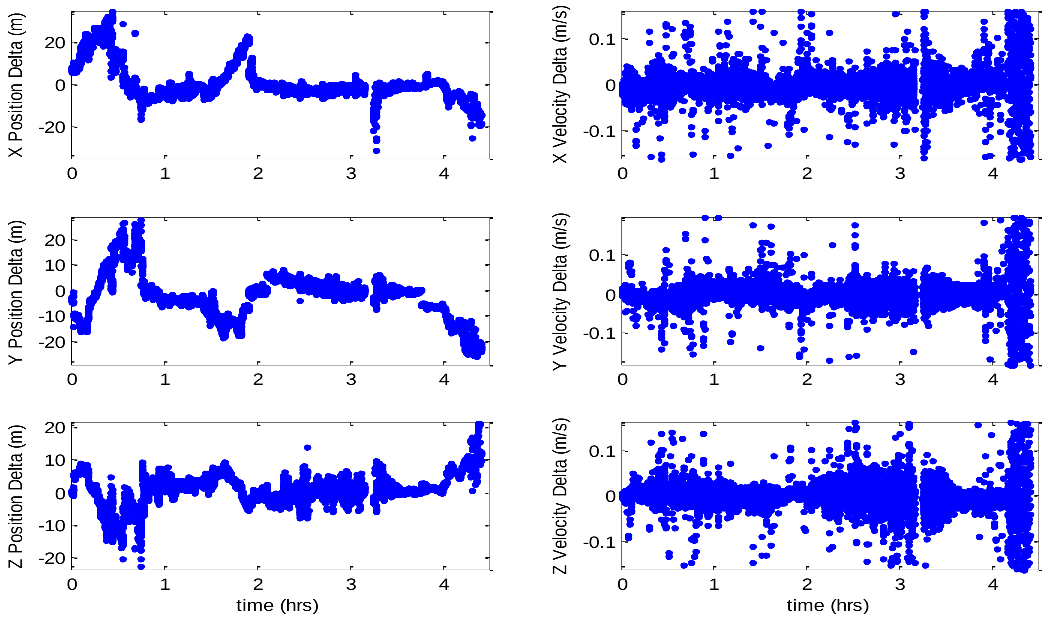

Figure 5 – Single point solution differences, uncorrected pseudo range vs Orion GPSR telemetry

The comparison using the corrected measurements, which included antenna path delays, is also shown:

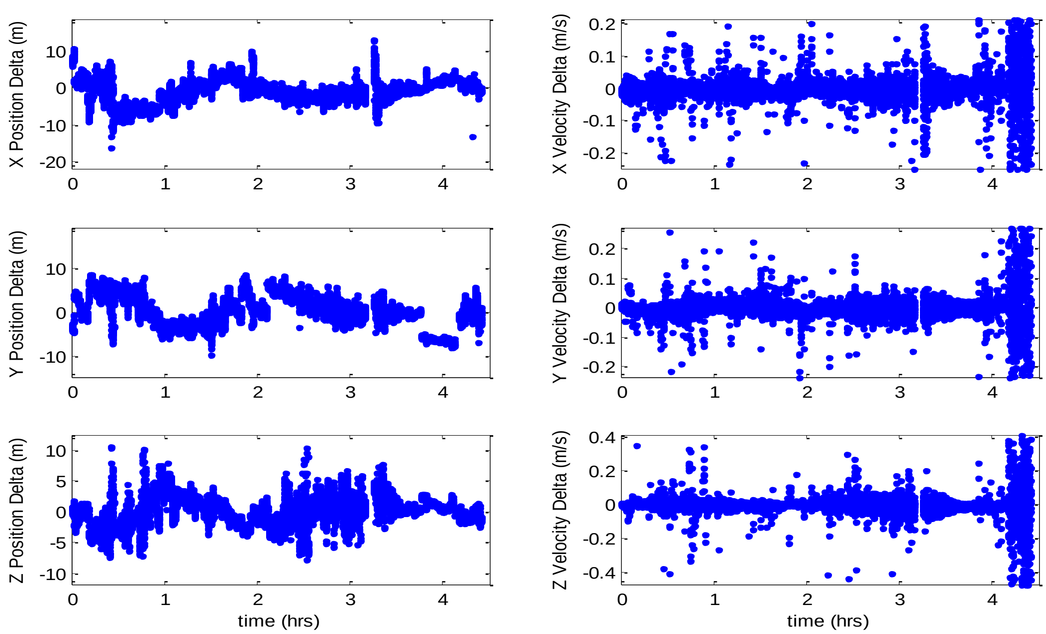

Figure 6 – Single point solution differences, corrected pseudo range vs Orion GPSR telemetry

Comparison of the orbit elements derived from telemetry verses that solved for in the single point solution (uncorrected measurements) is shown in Figure 7 and Figure 8.

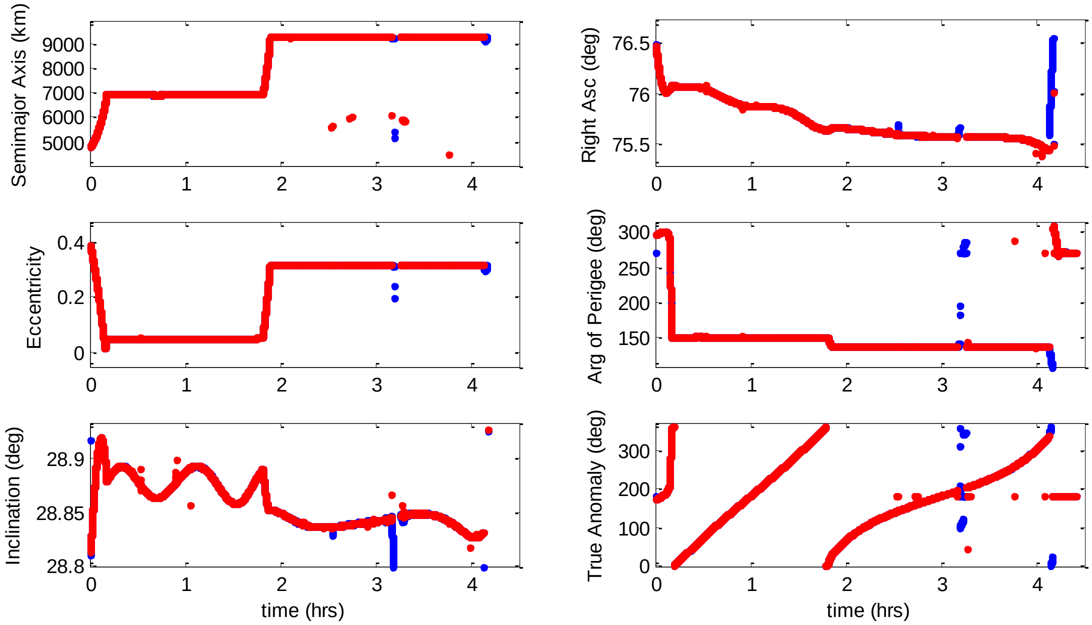

Figure 7 – Orbit elements for single point solution vs Orion GPSR telemetry

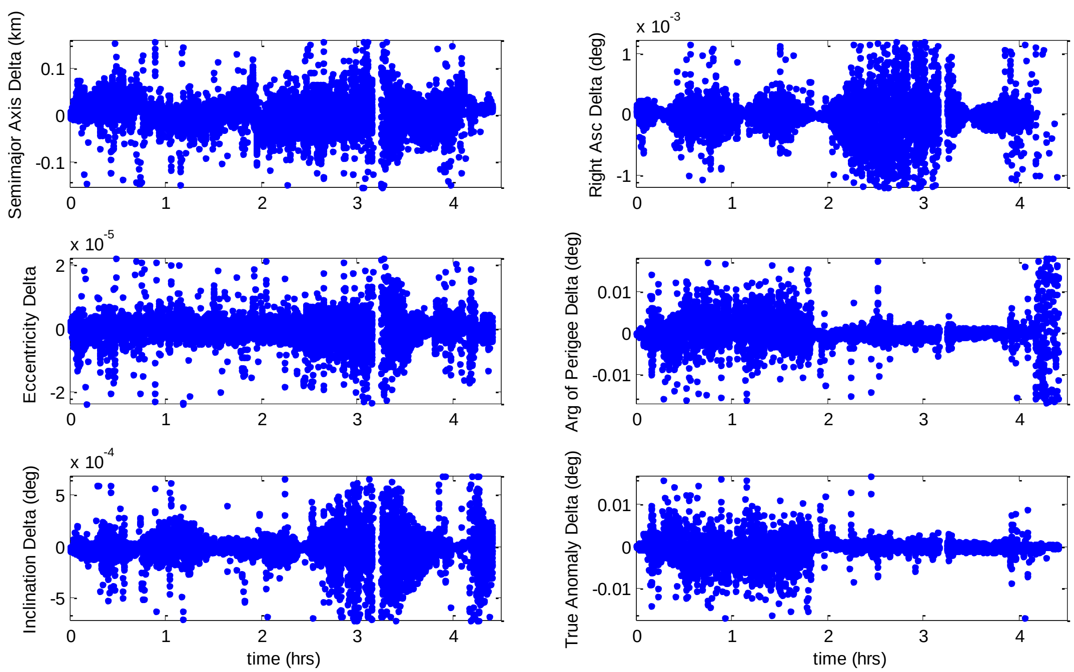

Figure 8 - Orbit element deltas for single point solution vs Orion GPSR telemetry

Filter Analysis/Comparison

The Orion GPSR measurements were processed using the NAVSIM POKEy filter. Bearing in mind that POKEy did not have attitude or thruster knowledge for Orion, and the Orion spacecraft was significantly out-gassing and thrusting throughout flight, process noise in the filter had to be appropriately tuned. The results are compared with the Orion telemetry GPSR solution in Figures 9-11.

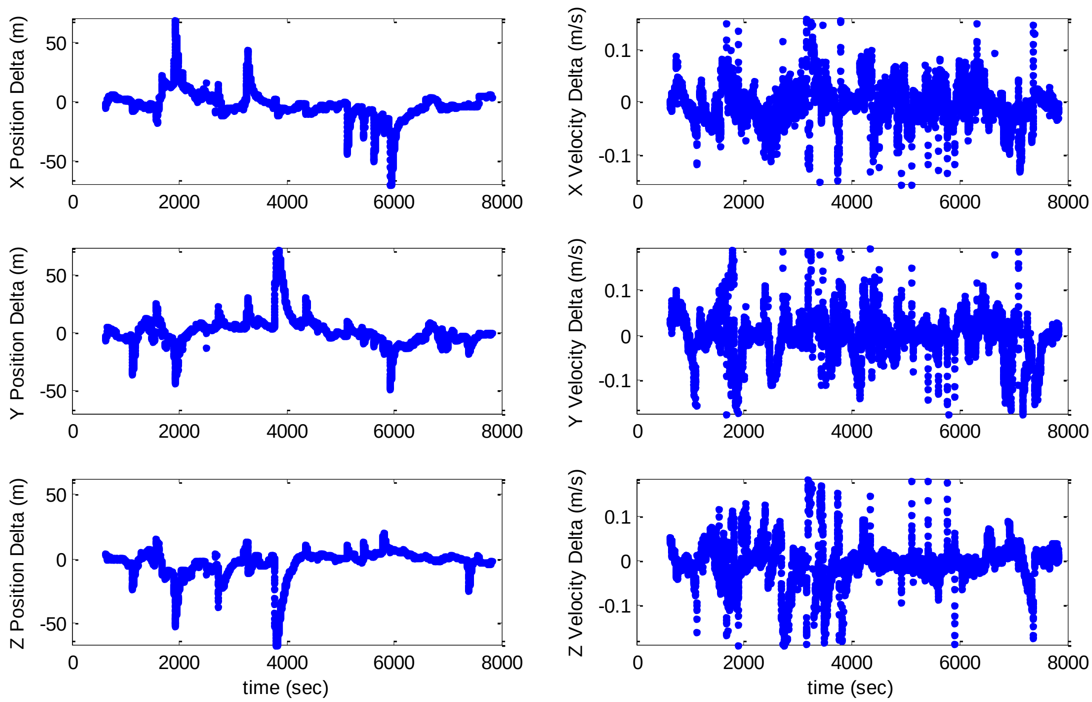

Figure 9 - NAVSIM POKEy filter solution vs Orion telemetry GPSR solution (position/velocity delta)

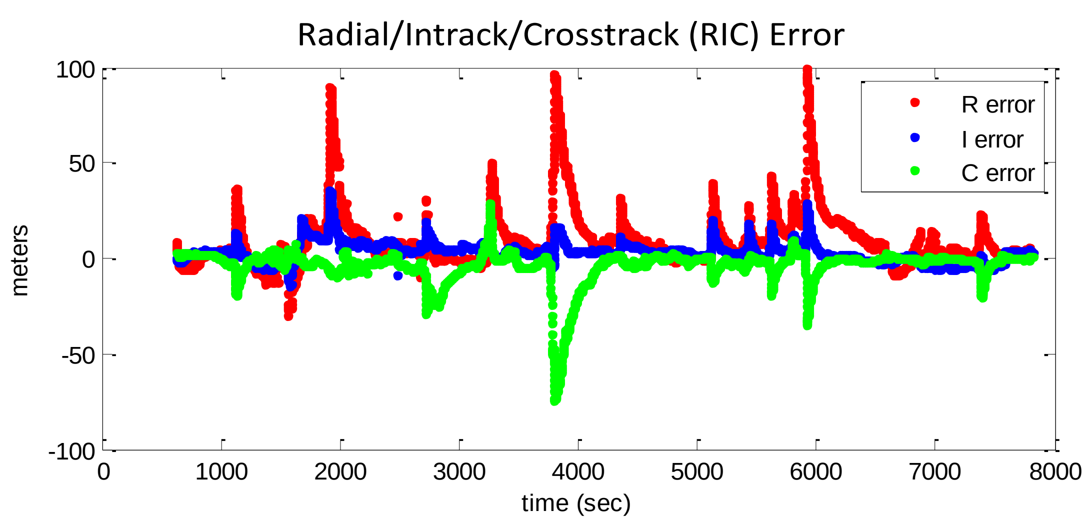

Figure 10 - NAVSIM POKEy filter solution vs Orion telemetry GPSR solution (RIC position delta)

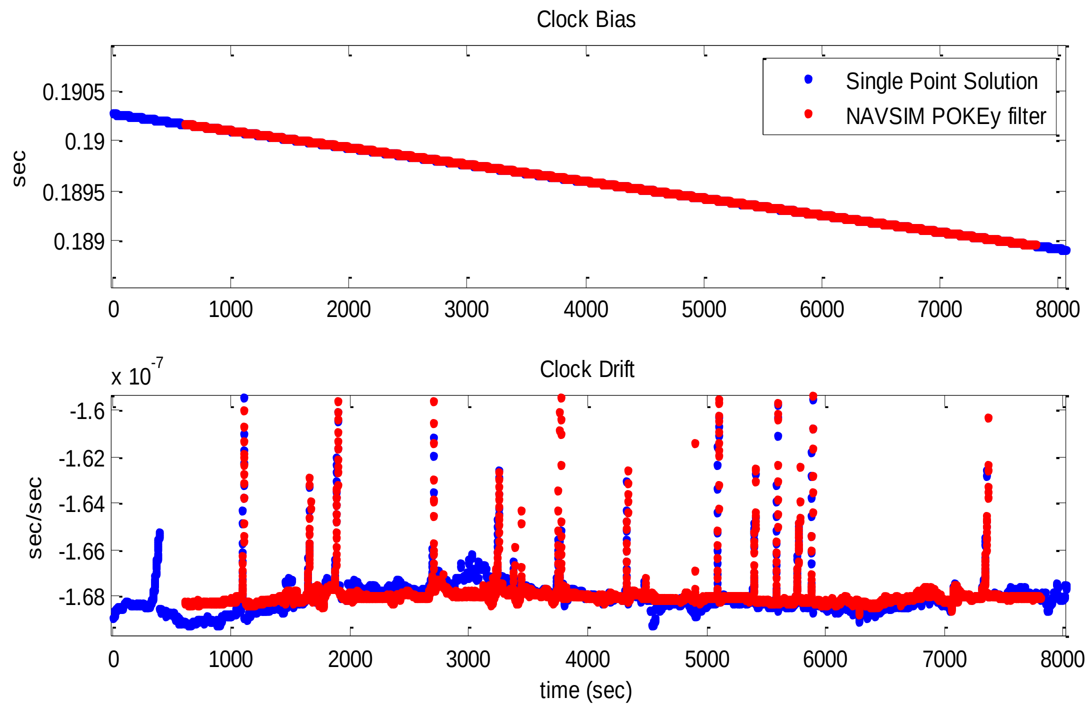

Figure 11 - NAVSIM POKEy filter solution vs Orion telemetry GPSR solution (clock)

Residual Analysis

POKEy filter residuals are shown in Figure 12 and Figure 13 for select GPS PRN's to illustrate the relationship between residuals (pre and post filter) and ionospheric/tropospheric model error. The upper-left plot in the figure shows measurement residual versus modeled ionospheric delay. The upper-right plot in the figure shows measurement residual versus modeled tropospheric delay. The lower-left plot in the figure shows measurement residual versus line-of-sight elevation angle. The lower-right plot in the figure shows measurement residuals, modeled ionospheric-delay, modeled tropospheric-delay, and variance versus time.

Figure 12 shows data from PRN13. From the data it can be seen that the models predict delays and the uncertainties in the models are used to increase measurement uncertainty. The variance is used to de-weight the measurement in the filter. Figure 13 shows data from PRN16. In this case the measurement data contains un-modeled ionospheric delay or other artifacts that cause residuals to exceed the measurement variance, potentially allowing noisy or biased measurements into the filter. Note that these un-modeled events can occur even at high elevation angles.

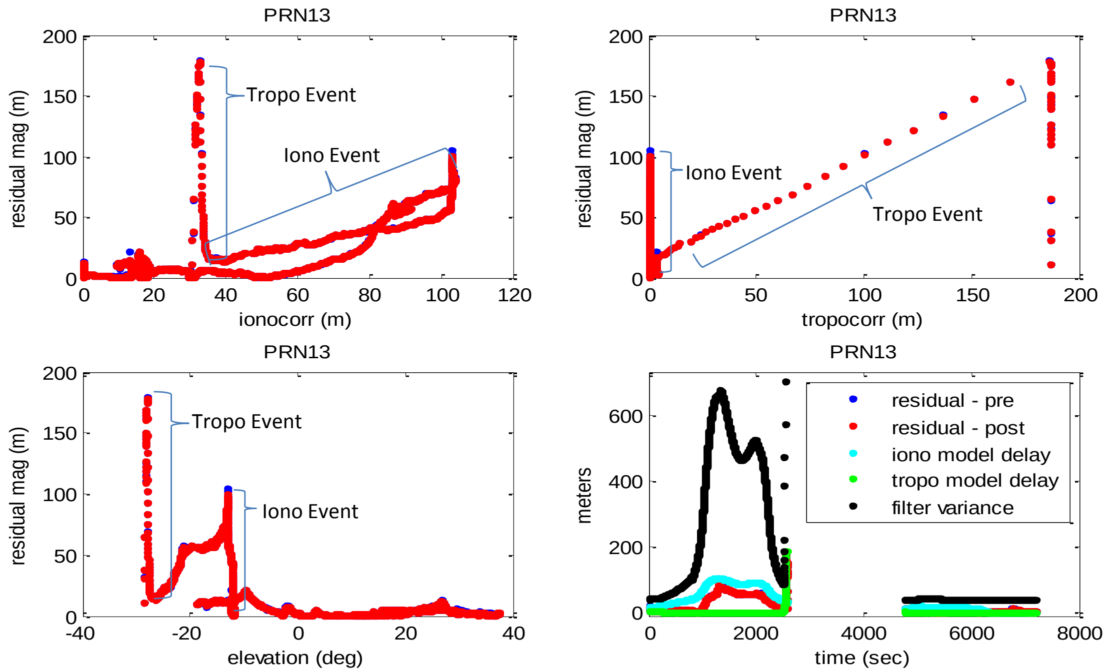

Figure 12 – PRN13 residuals

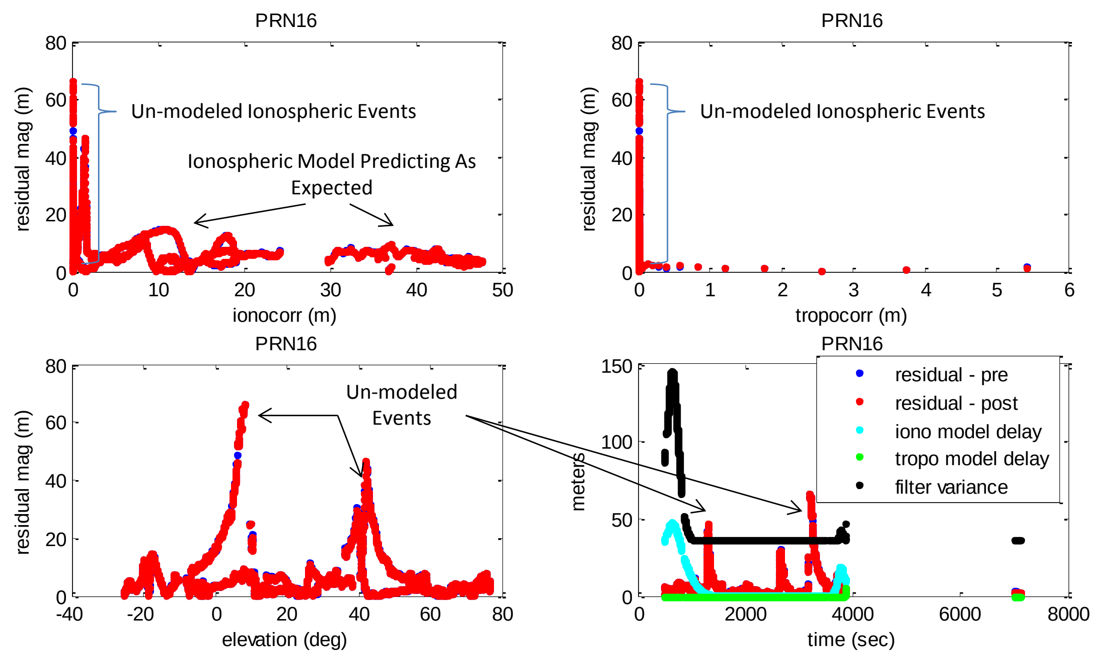

Figure 13 – PRN16 residuals

Fast Acquisition and High Altitude Tracking Results

One of the important design features of the Orion GPSR is its ability to perform fast acquisition of signals from a “cold start”, where it has no prior knowledge of its position, velocity, time, or the GPS constellation. The use of fast acquisition technology greatly simplified the task of integrating the GPSR and the Orion navigation software, eliminating the need for ground or onboard navigation systems to provide state vector or GPS constellation parameter data. The fast acquisition system is also required in order to rapidly acquire valid navigation measurements when returning from beyond LEO, and following entry plasma blackout. The aggressive time-to-first-fix (TTFF) capability of the GPSR is very important to overall Orion navigation system performance given the brief periods of exposure to strong signal environments during entry.

During EFT-1, the Orion GPSR was able to track 14 unique satellites within approximately one minute of the first exposure of the antennas to a live sky signal, following the jettison of the Launch Abort System (LAS). Prior to LAS jettison, the previous exposure to live sky signal had been several months prior to launch during vehicle buildup and checkout. During Orion development testing, a prototype GPSR was cold started twice during dynamic flight, as a piggyback payload on Orion CPAS (Capsule Parachute Assembly System) drop tests conducted from an Air Force C-17 at approximately 35,000 ft. The EFT-1 TTFF performance actually exceeded the performance observed during these drop tests, likely due to a much more benign angular rate and linear jerk environment when compared to that experienced during parachute testing. The in-flight fast acquisition performance was also consistent with extensive pre-flight hardware in the loop testing of both prototype and flight-like GPSRs.

In addition to the cold-start fast acquisition performance observed just after launch, the GPSR successfully tracked sufficient signals for navigation throughout the flight, including during the high altitude portions of the 2nd orbit, during which the vehicle remained above 3000km altitude for nearly two hours. Figure 14 shows the track history of the GPSR for the entire flight (left hand side), with a zoomed in box of the entry track performance in the lower right hand area. The red markers indicate the total number of signals in track (including identical signals tracked on both antennas), and the blue markers show the number of unique PRNs in track. The green line indicates the number of unique PRN measurement sets which passed all internal GPSR quality checks, including RAIM (Receiver Autonomous Integrity Monitoring); this line indicates the number of measurements that were made available to the Orion extended Kalman filter (EKF) for navigation state incorporation. For future flights, the Orion navigation team plans to evaluate all GPSR measurements internally (without relying on RAIM), in order to be able to use all available measurements even during periods of limited signal availability.

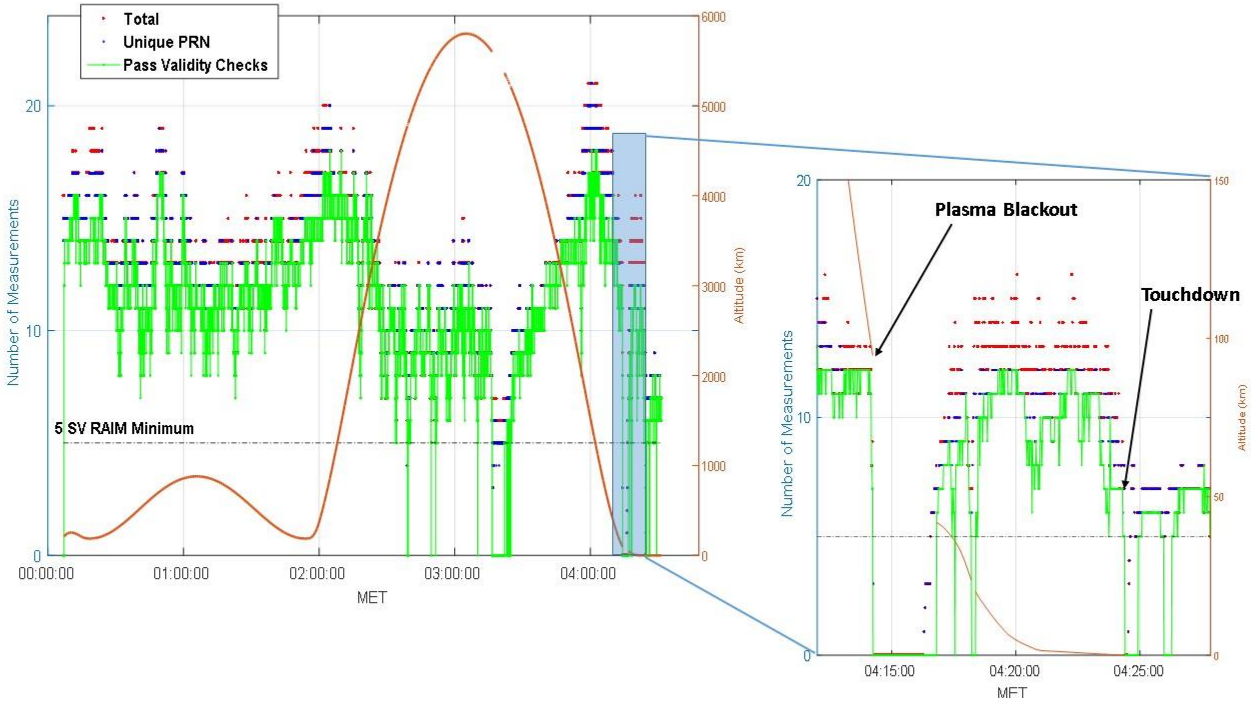

Figure 14: Satellite Track History vs. Mission Elapsed Time and Altitude

The green line on the left hand side of Figure 14 shows several brief dropouts of "valid" signals that occurred during high altitude flight; these were primarily a result of brief periods of time where there were insufficient number of satellites available to perform RAIM, however there was also some unusual GPSR clock behavior which seems to have prevented the GPSR from correctly identifying valid measurements during a few minutes of high altitude flight. This issue has already been addressed in a software fix which better manages internal clock drift estimates during periods of reduced signal availability. Post-processing of the measurement data without regard to the GPSR's internally computed measurement health status showed that the longest continuous period of high-altitude flight without at least four usable satellite measurements was about 30 seconds. High altitude performance during flight greatly exceeded preflight hardware in the loop simulation performance and lends high confidence to the ability of the GPS to provide usable measurements to the navigation system during operations well beyond LEO.

The lower-right portion of Figure 14 shows the short entry plasma blackout, which occurred between 95km and 42km altitude. This brief blackout and quick re-acquisition allowed for more than seven minutes of valid GPS measurements to be delivered to the Orion navigation system during atmospheric flight, enabling the vehicle navigation state to converge nicely prior to touchdown thereby facilitating a successful wind-relative touchdown orientation maneuver. Drogue and main parachute deployment dynamics had minimal impact on GPS tracking performance, as predicted by prototype GPS performance during capsule drop tests. This atmospheric entry performance is an important validation of the drop test results, as GPS tracking performance during plasma and dynamic parachute events proved difficult to model during hardware in the loop testing.

Summary of Results

Independent analysis of the Orion EFT-1 flight data confirms the GPSR is functioning properly and providing good measurement data to the Orion on-board filter. During the course of the analysis, a few areas for improvement were identified.

First, the Orion GPSR measurement data time stamps are telemetered in GPS time with the GPSR clock bias already subtracted from the GPSR time stamp. The separately telemetered clock bias is of insufficient precision to fully reproduce the original GPSR time stamp, presenting challenges in filtering the measurement data, regardless of whether one is processing the uncorrected measurements or the corrected measurements.

Second, the Orion on-board Klobuchar ionospheric delay model exhibits discontinuities that introduce themselves into the corrected measurements. Changes to model design are being considered.

Third, some internal clock handing issues occurred during high altitude flight which prevented the GPSR from correctly identifying valid measurements during a brief portion of high altitude flight; a preliminary software fix for this issue has already been delivered but further investigation is being conducted now in order to ensure that the GPSR can reliably deliver valid measurements to Orion navigation during flight beyond LEO.

Conclusion

This paper presented a brief description of the Orion EFT1 GPS navigation system, an independent analysis of flight telemetry data, and evaluation of the GPSR performance, including evaluation of the ionospheric model employed to supplement the single frequency receiver. Independent analysis of the Orion EFT-1 flight data confirms the GPSR is functioning properly and providing good measurement data to the Orion on-board filter.

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